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A Holistic Approach to Networked Information Systems Design and Analysis

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The work funded under this award established methods and tools for secure and timely delivery of information over wireless communication networks. Our methods enable the wireless networking and storage systems to provide provable performance guarantees for a variety of diverse applications that impose strict delay, throughput, reliability, and availability requirements. Our contribution includes provably secure wireless networking protocols as well as a methodology for design and analysis of prov- ably correct and safe design of heterogeneous systems. We have designed mechanisms that ensure insensitivity to strategic gaming and security against malicious adversaries. Our research paves the way to a holistic theory that unifies a range of mathematical, system-theoretic, and optimization tools. Our research will have a major impact on future aerial systems that will support secure, robust, and delay-sensitive applications.

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A Holistic Approach to Networked Information Systems Design and Analysis

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Abstract

The work funded under this award established methods and tools for secure and timely delivery of information over wireless communication networks. Our methods enable the wireless networking and storage systems to provide provable performance guarantees for a variety of diverse applications that impose strict delay, throughput, reliability, and availability requirements. Our contribution includes provably secure wireless networking protocols as well as a methodology for design and analysis of provably correct and safe design of heterogeneous systems. We have designed mechanisms that ensure insensitivity to strategic gaming and security against malicious adversaries. Our research paves the way to a holistic theory that unifies a range of mathematical, system-theoretic, and optimization tools. Our research will have a major impact on future aerial systems that will support secure, robust, and delay-sensitive applications.

Summary of Contributions

Our research has made the following contributions:

1. A system-theoretic clean slate approach to provably secure ad hoc wireless networks. The approach provides a complete protocol suite with provable guarantees, as well as a proof of min-max optimality with respect to any given utility function of source-destination rates.

2. Scheduling policies that satisfy the inter-delivery requirements for clients with heterogeneous channel conditions. We have developed optimal policies, which are intuitively appealing and easily implementable, and proposed low-complexity algorithms to identify optimal policies.

3. Characterization and optimization of delay guarantees for real-time multimedia traffic flows in wireless networks. We have developed a simple but accurate enough analytical model for predicting the queueing delay of real-time multimedia traffic flows.

4. Autonomous intersection management framework for smart transportation systems. We have designed vehicle-to-vehicle (V2V) coordination and vehicle-to-infrastructure rules, and have established the system-wide safety and liveness of the autonomous traffic.

5. Fluctuation analysis of debt based policies for wireless networks. We have introduced a path-wise cost function based on the law of the iterated logarithms and showed that a debt-based policy is optimal.

6. Optimal determination of source-destination connectivity in random graphs. We proposed an optimal policy for determining source-destination connectivity in random graphs.

7. Mechanisms for management of cellular data networks. We have designed incentive compatible algorithms that can be used to attain optimal network scheduling and traffic management.

8. Incentive mechanisms for cooperative behavior in device-to-device wireless networks. We designed an incentive framework that promotes such cooperation co-located wireless devices, while ensuring good quality of service.

9. Design efficient algorithms that leverage the new technique of network coding in multi-hop wireless networks. Our algorithms strike the optimal trade-off between the delay and the required number of transmissions.

10. Incentivizing optimal behavior in societal networks. We developed an architecture to promote the attainment of desired behavior in large scale networks with a shared resource component, such as electricity networks. We show that our scheme can attain quite substantial savings.

11. Optimal algorithms for energy harvesting in wireless networks. We use a Markov-decision-process (MDP) based approach to obtain optimal policies for transmissions. The key advantage of our approach is that it holistically considers information and energy in a single framework.

12. Analysis of fork-joint systems for in-network computation. We have developed a highly versatile and accurate algorithm for estimating the response time in this system.

13. Control algorithms for time-varying systems; We have developed an approximate dynamic programming algorithm whose performance is extremely close to the optimal and which performs significantly better than greedy algorithms, Lyapunov optimization based online algorithms, certainty equivalent based methods, and naive approaches using historic data

14. Development of secure, reliable, and hidable communication schemes. We have developed information-theoretically secure schemes that can protect information against a malicious adversary or eavesdropper.

15. Architectures for Software-Defined wireless networks. We defined a set of wireless abstractions that drastically simplify the process of developing applications for integrated wireless and wireline network environments.

Detailed Description

A System-Theoretic Clean Slate Approach to Provably Secure Ad Hoc Wireless Networking. Traditionally, wireless network protocols have been designed for performance. Subsequently, as attacks have been identified, patches have been developed. This has resulted in an "arms race" development process of discovering vulnerabilities and then patching them. The fundamental difficulty with this approach is that other vulnerabilities may still exist.

No provable security or performance guarantees can ever be provided. We have developed a system-theoretic approach to security that provides a complete protocol suite with provable guarantees, as well as a proof of min-max optimality with respect to any given utility function of source-destination rates [C11,C12,C13,J13]. Our approach is based on a model capturing the essential features of an ad-hoc wireless network that has been infiltrated with hostile nodes. We consider any collection of nodes, some good and some bad, possessing specified capabilities vis-a-vis cryptography, wireless communication and clocks. The good nodes do not know the bad nodes. The bad nodes can collaborate perfectly, and are capable of any disruptive acts ranging from simply jamming to non-cooperation with the protocols in any manner they please. The protocol suite caters to the complete life-cycle, all the way from birth of nodes, through all phases of ad hoc network formation, leading to an optimized network carrying data reliably. It provably achieves the min-max of the utility function, where the max is over all protocol suites published and followed by the good nodes, while the min is over all Byzantine behaviors of the bad nodes. Under the protocol suite, the bad nodes do not benefit from any actions other than jamming or cooperating. This approach supersedes much previous work that deals with several types of attacks including wormhole, rushing, partial deafness, routing loops, routing black holes, routing gray holes, and network partition attacks.

Packet Inter-Delivery Time Optimization in Cyber-Physical Systems. In cyber-physical systems, data from sensor nodes should be delivered to other consumer nodes such as actuators in a regular fashion. But, in practical systems over unreliable media such as wireless, it is a significant challenge to guarantee small enough inter-delivery times for different clients with heterogeneous channel conditions and inter-delivery requirements. Motivated by this, we have designed scheduling policies aiming at satisfying the inter-delivery requirements of such clients. We have formulated the problem as a risk-sensitive Markov Decision Process (MDP) Although the resulting problem involves an infinite state space, we proved that there is an equivalent MDP involving only a finite number of states. Then we have proved the existence of a stationary optimal policy and established an algorithm to compute it in a finite number of steps. However, the bane of this and many similar problems is the resulting complexity, and, in an attempt to make fundamental progress, we have further proposed a new high reliability asymptotic approach. In essence, this approach considers the scenario when the channel failure probabilities for different clients are of the same order, and asymptotically approach zero. We thus proceeded to determine the asymptotically optimal policy: in a two-client scenario, we have shown that the asymptotically optimal policy is a "modified least time-to-go" policy, which is intuitively appealing and easily implementable; in the general multi-client scenario, we are led to an SN policy, and we have developed an algorithm of low computational complexity to obtain it. Simulation results show that the resulting policies perform well even in the pre-asymptotic regime with moderate failure probabilities.

Characterization and Optimization of Delay Guarantees for Real-time Multimedia Traffic Flows in Wireless Networks. Due to the rapid growth of real-time applications and the ubiquity of IEEE 802.11 MAC as a layer-2 protocol for wireless local area networks (WLANs), it has become increasingly important to support delay-based quality of service (QoS) in such WLANs. We have developed a simple but accurate enough analytical model for predicting the queueing delay of real-time multimedia traffic flows in non-homogeneous random access based WLANs [J4]. This leads to tractable analysis for meeting queueing delay specifications of a number of flows. In particular, we have addressed the feasibility problem of whether the mean delays required by a set of User Datagram Protocol (UDP) flows supporting real-time multimedia traffic can be guaranteed in WLANs. Based

on the model and feasibility analysis, we have further developed an optimization technique to minimize the delays for the traffic flows. Moreover, we have presented a decentralized algorithm and and have presented extensive simulation and experimental trace-based results to demonstrate the accuracy of our model and the performance of the algorithms.

Autonomous intersection management framework for smart transportation systems. An important area of cyber-physical systems research is the development of smart transportation systems due to their potentially significant impact on safety, the economy, and the environment. We have proposed an approach based on Model Predictive Control (MPC) for the development, in the first instance, of provably collision free autonomous ground transportation systems, and have presented an autonomous intersection management framework. The MPC approach enables a vehicle to generate its own motion locally in time based on an optimization framework, incorporating constraints based on the states of other vehicles in the neighborhood, the speed limit of a road, the maximum values of acceleration and deceleration, etc. Safety and liveness of the traffic are however system-wide properties, not merely neighborhood properties, and the challenge is to augment this distributed optimization with coordination rules that guarantee overall system-wide safety as well as liveness of the traffic. We have designed two vehicle-to-vehicle (V2V) coordination rules, along with a vehicle-to-infrastructure rule, and have established the system-wide safety and liveness of the autonomous traffic based on each vehicle's MPC motion planner, operating in conjunction with an algorithm that orders vehicles according to their runtime properties.

Fluctuation analysis of debt based policies for wireless networks. We analyzed wireless networks where clients served by an access point require a timely throughput of packets to be delivered by hard per-packet deadlines, and proved the timely-throughput optimality of certain debt-based policies. To make facilitate support of real time applications, we have introduced a path-wise cost function based on the law of the iterated logarithm, studied in fluctuation theory, which captures the deviation from a steady stream of packet deliveries and showed that a debt-based policy is optimal [C38].

Optimal determination of source-destination connectivity in random graphs. We have investigated the problem of optimally determining source-destination connectivity in random graphs [C39,JR4]. We have considered the classic Erdos-Renyi (ER) random graph, where an edge independently exists between any two nodes. We have examined the problem of determining as rapidly as possible whether a given pair of nodes, a source S and a destination D, are connected by a path, assuming that at each step one edge can be tested to see if it exists or not. We have determined an optimal policy that minimizes the total expected number of steps. The optimal policy has several interesting features. In order to establish connectivity of S and D, a policy needs to check all edges on some path to see if they all exist, but to establish disconnectivity it has to check all edges on some cut to see if none of them exists. The optimal policy has the following form. At each step it examines the condensation multigraph formed by contracting each known connected component to a single node, and then checks an edge that is simultaneously on a shortest $S - D$ path as well as in a minimum $S - D$ cut. Among such edges, it chooses that which leads to the most opportunities for connection. Interestingly, the optimal strategy does not depend on the probability p of an edge or the number n of nodes, even though the entire graph itself undergoes a sharp transition from disconnectivity to connectivity around $p = \ln n$. The policy is efficiently implementable, requiring no more than $30 \log 2n$ operations to determine which edge to test next. The result also extends to some more general graphs.

Mean Field Games and Network Management. A theme common to many scheduling and traffic management schemes is the reliance on using self-reported state for decision making. In keeping with the project theme of ensuring correctness and optimal performance, we challenge the assumption of accurate self-reported system state. Thus, we aim at designing systems that incentivize users to report in such a way that system performance is optimal. In work under this theme [C37], we aimed at developing incentive compatible algorithms that can be used to attain optimal network traffic management goals. In a system with multiple queues and a single server, an algorithm that is well known to yield low latency is longest queue first (LQF) However, when queues are asked to declare their respective sizes, they have an incentive to declare large queues in the hope of receiving service. We studied an auction theoretic version of this problem wherein the queues bid for service. The question is whether the resulting schedule would possess the good properties of LQF? We consider a system in which auctions are used at each server to decide which queue to serve at that time instant. The users model their opponents through a distribution of their bids, and take the best response against that assumption. We show that there exists a mean field equilibrium in this setting, i.e., there exists a bid distribution such that the assumed distribution would be consistent with each players actions, resulting int he same distribution. We show further, that the actual service regime turns out to be longest queue first. Thus, the scheme is optimal from a net system utility perspective since it results in short queue lengths. We also show using simulations that the equilibrium is simple to compute.

Incentives for Co-operation in D2D Networks. In this work [C6], we consider the problem of streaming live content to a cluster of co-located wireless devices that have both an expensive unicast base-station-to-device (B2D) interface, as well as an inexpensive broadcast device-to-device (D2D) interface, which can be used simultaneously. Our setting is a streaming system that uses a block-by-block random linear coding approach to achieve a target percentage of on-time deliveries with minimal B2D usage. Our goal is to design an incentive framework that would promote such cooperation across devices, while ensuring good quality of service. Based on ideas drawn from truth-telling auctions, we design a mechanism that achieves this goal via appropriate transfers (monetary payments or rebates) in a setting with a large number of devices, and with peer arrivals and departures. Here, we show that a Mean Field Game can be used to accurately approximate our system. Furthermore, the complexity of calculating the best responses under this regime is low. We implement the proposed system on an Android testbed, and illustrate its efficient performance using real world experiments.

Leverage the Network Coding technique to minimize delays and the number of transmissions in Wireless Systems. As we approach an era of ubiquitous computing with information transmitted through multiple wireless devices, we are faced with the challenge of prudently consuming power in those devices while ensuring low latency. To address this trade-off between reducing transmissions and lowering latency, we consider a network-coding setting with the objective of minimizing transmission and latency costs in [J14,J15]. If packets exist that are destined in opposite directions at a particular node, the "reverse carpooling" effect can be exploited to obtain savings. However, if packets are destined in a single direction, the question is whether the node should wait for further packets to arrive, or to go ahead an transmit to avoid delays. We define a cost function as a convex combination of the two parameters, and use a dynamic programming frame work to determine what the form of the optimal algorithm would be. We show that it takes a appealing threshold form

in two different problem settings. We illustrate using simulations that the performance of such a threshold scheme is good even in a multihop setting.

Incentivizing Optimal Behavior in Societal Networks. We considered the problem of a Load Serving Entity (LSE) trying to reduce its exposure to electricity market volatility by incentivizing demand response in a Smart Grid setting [C3,C4]. We focused on the day-ahead electricity market, wherein the LSE has a good estimate of the statistics of the wholesale price of electricity at different hours in the next day, and wishes its customers to move a part of their power consumption to times of low mean and variance in price. Based on the time of usage, the LSE awards a differential number of "Energy Coupons" to each customer in proportion to the customer's electricity usage at that time. A lottery is held periodically in which the coupons held by all the customers are used as lottery tickets.

Our study takes the form of a Mean Field Game, wherein each customer models the number of coupons that each of its opponents possesses via a distribution, and plays a best response pattern of electricity usage by trading off the utility of winning at the lottery versus the discomfort suffered by changing its usage pattern. The system is at a Mean Field Equilibrium (MFE) if the number of coupons that the customer receives is itself a sample drawn from the assumed distribution. We show the existence of an MFE, and characterize the mean field customer policy as having a multiple-threshold structure in which customers who have won too frequently or infrequently have low incentives to participate. We then numerically study the system with a candidate application of air conditioning during the summer months in the state of Texas. Besides verifying our analytical results, we show that the LSE can potentially attain quite substantial savings using our scheme. Our techniques can also be applied to resource sharing problems in other *societal* networks such as transportation or communication.

Energy-Harvesting in Wireless Networks. While sensor networks are all-pervasive with information transmitted through multiple wireless devices, we are faced with the challenge of managing power consumption in nodes while ensuring high availability and low latency. In [J15] we consider energy-harvesting as a means to improve the longevity of nodes and obtain the availability of sensors, while in [J8] we consider scheduling issues in relay networks to address energy harvesting and throughput trade-off. To obtain expressions for availability and latency in [J15], we use a stochastic fluid flow model to analyze the battery level via a semi-Markov process approach leveraging upon results in [J17] and [JR3]. Then, using a Markov-decision-process (MDP) based approach we obtain optimal policies for transmissions. While we model using two tiers, one for the information flow and the other for energy flow, by employing multiple time-scales, we were able to abstract essential features of one tier which get passed on to the other tier and this process is iterated. Thus we holistically considered information and energy in a single framework, and that is the key novelty in our work.

Response Times in Fork-Join Queues. We considered a parallel processing queueing system motivated by in-network function computing scenarios [W6]. An arriving job to this system is instantaneously partitioned into tasks, all of which are processed in parallel and need to be completed to finish processing the job. Jobs arrive into this system at random time intervals. If a task belonging to an arriving job finds that task of another job being processed, it will wait in queue for its turn to be processed. This queueing system has been a topic of interest for many researchers since the 1980s, and is called the fork-join queueing system. It has widespread applications in sensor networks, health care systems and computer systems. The quantity of interest in this scenario is the average time spent in the system

by a job, known as the response time. We come up with a conjecture and use it to develop an algorithm for estimating this response time [W7]. This algorithm is highly versatile and accurate, much more so than any other algorithm available in literature for this 30 year old problem.

Managing Cyclically Time-varying Systems. In most computer-communication systems (including datacenters which is our case study), supply, demand and cost are time-varying and stochastic. Developing control algorithms to efficiently operate such systems such systems are difficult since provably optimal results can only be obtained for stationary systems. In [J7] (where number of nodes are scaled up) and [W12] (where number of classes are scaled up), we take a two-stage approach. In the first stage we create a time-stable performance at each server although the number of servers could be time-varying. Then we do routing and traffic splitting so that cost is minimized. However, in [J18] and [C35] we incorporate the time element as part of the system state and build a 5-dimensional state MDP. However, due to curse of dimensionality which is exacerbated because of the continuous nature of elements of the state-space vector, we develop an approximate dynamic programming algorithm that we call one-step rollout algorithm (ORA) We show that ORA results in an optimal solution extremely close to the MDP. Further, ORA performs significantly better than greedy algorithms, Lyapunov optimization based online algorithms, certainty equivalent based methods, and naive approaches using historic data.

Secure, reliable, and hidable communication schemes. We focused on the design and analysis of efficient and secure network coding schemes for wireless and storage networks [C25,C29,C33,C36,C40]. The goal of this effort was to design information-theoretically secure schemes that can protect information against a malicious adversary or eavesdropper. We leverage advanced coding schemes, such as regenerative coding to achieve this goal. We focus on the design of coding schemes that achieve weak security, i.e., prevent the adversary from being able to obtain information about any individual file in the system. The weak security is a low-overhead light-weight approach for protecting users' data. In contrast to traditional information-theoretic and cryptographic tools, it does not require exchange of secure keys and does not reduce the capacity of the network. We have also developed deniable and hidable coding schemes. With deniable coding schemes the adversary is not able to reliably decide whether or not the communication is taking place on the channel. In a hidable scheme, the adversary will not be able to learn any information about the transmitted message.

Principled wireless support for software-defined networks. The networking industry is in the midst of a transformation due to the Software Defined Networking (SDN) paradigm, with the Open Networking Foundation (ONF) leading the way to standardize the OpenFlow (OF) protocol, which could lead the way to multi-vendor data plane compatibility. While the SDN approach has significant benefits for both wireline and wireless networks, most of the attention of the research community has focused on wireline networks, with wireless networks receiving only a scarce attention. The popular SDN standards, such as OpenFlow, do not provide support for wireless protocols, which limits the ability to develop SDN applications that include wireless components. Accordingly, we defined a set of wireless abstractions that drastically simplify the process of developing applications for integrated wireless and wireline network environments. We proposed extensions of the OpenFlow protocol that would allow it to control IEEE 802.11 devices, query their status, receive notifications, and configure radio interfaces [C24,C26]. More specifically, we addressed the following key research questions: (a) How to perform capability extensions of an SDN protocol for aerial networks? (b) How

to simplify developing SDN applications without giving up fine-grain device control? (c) How to analyze the performance of an SDN application and its configuration for an aerial network? (d) How to test, benchmark, and verify an experimental setup?

Conference papers

C1. P. Goshal, J. Casey, P. Gratz, and A. Sprintson. "Stochastic Pre-Classification for Software Defined Firewalls", In Proceedings of International Conference on Computer Communications and Networks (ICCCN), Nassau, Bahamas, July-August 2013

C2. J. Casey, A. Sutton, G. Dos Reis and A. Sprintson. "Eliminating Network Protocol Vulnerabilities Through Abstraction and System Language Design." In Proceedings of The 3rd International Workshop on Rigorous Protocol Engineering (WRiPE 2013), Gottingen, Germany, October 2013

C3. I-H. Hou, Y. Liu, and A. Sprintson, "A Non-Monetary Protocol for Wireless Peer-to-Peer Content Distribution with Network Coding," 2013 International Symposium on Modeling and Optimization in Mobile, Ad Hoc, and Wireless Networks (WiOpt), May 2013

C4. J-Y Won, P.V. Gratz, S. Shakkottai and J. Hu, "Having Your Cake and Eating It Too: Energy Savings Without Performance Loss Through Resource SharingDriven Power Management," International Symposium on Low Power Electronics and Design, 2015

C5 Xi Liu and P. R. Kumar, "Towards Safety of Transportation Systems with a Mixture of Automated and Human-Driven Vehicles." *Workshop on Intelligent Transportation Systems (ITS)*, 8th International Conference on Communication Systems & Networks (COMSNETS 2016), January 5–9, 2016. (Invited Paper)

C6. J. Li, R. Bhattacharyya, Suman Paul, S. Shakkottai and V. Subramanian, "Incentivizing Sharing in Realtime D2D Streaming Networks: A Mean Field Game Perspective," in IEEE Infocom 2015, Hong Kong, China.

C7. J. Li, B. Xia, X. Geng, H. Meng, S. Shakkottai, V. Subramanian and L. Xie, "Mean Field Games in Societal Networks," Information Theory and Applications Workshop 2015, San Diego, CA.

C8. J. Li, B. Xia, X. Geng, H. Meng, S. Shakkottai, V. Subramanian and L. Xie, "Energy Coupon: A Mean Field Game Perspective on Demand Response in Smart Grids," Sigmetrics 2015, Portland, OR, 2015

C9. Rahul Singh, Xueying Guo and P. R. Kumar, "Index Policies for Optimal Mean-Variance Trade-Off of Inter-delivery Times in Real-Time Sensor Networks," in Proceedings of IEEE INFOCOM 2015: The Conference on Computer Communications, Hong Kong, April 26May 1, 2015

C10. Xueying Guo, Rahul Singh, P. R. Kumar and Zhisheng Niu,"A High Reliability Asymptotic Approach for Packet Inter-Delivery Time Optimization in Cyber-Physical Systems." *Proceedings of The 16th ACM International Symposium on Mobile Ad Hoc Networking and Computing, ACM MobiHoc 2015*, June 22-25, 2015, Hangzhou, China.

C11. Jonathan Ponniah, Yih-Chun Hu and P. R. Kumar, "A Clean Slate Design for Secure Wireless Ad-Hoc Networks - Part 1: Closed Synchronized Networks." pp. 175-182, *Proceedings of the 13th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, WiOpt 2015*, May 25-29, 2015, Mumbai, India.

C12. Xueying Guo, Rahul Singh, P. R. Kumar and Zhisheng Niu, "Optimal Energy-Efficient Regular Delivery of Packets in Cyber-physical Systems," To appear in IEEE International Conference on Communications (ICC), London, UK, June 8-12, 2015

C13 Jonathan Ponniah, Yih-Chun Hu and P. R. Kumar, "A Clean Slate Approach to the Design of Secure Wireless Ad-Hoc Networks." Submitted to Proceedings of the 2015 IEEE International Symposium on Information Theory (ISIT 2015), June 14-19, 2015, Hong Kong. Submitted January 23, 2015

C14. Rahul Singh and P. R. Kumar, "Optimizing Quality of Experience of Dynamic Video Streaming Over Fading Wireless Networks." To appear in *Proceedings of 54th IEEE Conference on Decision and Control*, December 15–18, 2015, Osaka, Japan.

C15 Rahul Singh and P. R. Kumar, "Decentralized Throughput Maximizing Policies for Deadline-Constrained Wireless Networks." To appear in *Proceedings of 54th IEEE Conference on Decision and Control*, December 15–18, 2015, Osaka, Japan. (Invited Paper)

C16. Simon Yau, Liang Ge, Ping-Chun Hsieh, I-Hong Hou, Shuguang Cui, P. R. Kumar, Amal Ekbal, Nikhil Kundargi, "WiMAC: Rapid Implementation Platform for User Definable MAC Protocols Through Separation." *SIGCOMM 2015 Demos*, August 17-21, 2015, London, United Kingdom.

C17. Jonathan Ponniah, Yih-Chun Hu and P. R. Kumar, "A Clean Slate Design for Secure Wireless Ad-Hoc Networks - Part 2: Open Unsynchronized Networks." pp. 183-190, *Proceedings of the 13th International Symposium on Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks, WiOpt 2015*, May 25-29, 2015, Mumbai, India.

C18. Chan, W.H.R., Zhang, P., Zhang, W., Nevat, I., Valera, A.C., Tan, H.-X. and Gautam, N. "Adaptive Duty Cycling in Sensor Networks via Continuous Time Markov Chain Modeling," Proc. of the IEEE International Conference on Communications (ICC), 6669-6674.

C19. Ying, Y., Birke, R., Wang, C., Chen, L.Y. and Gautam, N. "Optimizing Energy, Locality and Priority in a MapReduce Cluster," Proc. of IEEE Intl. Conf. on Autonomic Computing (ICAC), 21-30, 2015

C20. A. Heidarzadeh and A. Sprintson, "Cooperative Data Exchange with Unreliable Clients," to appear in Proceedings of the 53th Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, USA, Sep-Oct 2015

C21. S. Kadhe, E. Soljanin, and A. Sprintson, "When do the Availability Codes Make the Stored Data More Available," to appear in Proceedings the 53th Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, USA, Sep-Oct 2015

C22. S. H. Dau, W. Song, A. Sprintson, and C. Yuen, "Constructions of MDS Codes via Random Vandermonde and Cauchy Matrices over Small Fields," to appear in Proceedings of the 53th Annual Allerton Conference on Communication, Control, and Computing, Monticello, Illinois, USA, Sep-Oct 2015

C23 J. Casey, M. Yan, C. Chojnacki, and A. Sprintson, "Flowsim: Interactive SDN Switch Visualization," to appear in Proceedings of IEEE Conference on Network Function Virtualization and Software Defined Networks, demo track, November, 2015

C24. P. Shome, M. Yan, S. Najafabadi, N. Mastronarde, and A. Sprintson, "CrossFlow: A Cross-layer Architecture for SDR Using SDN Principles," to appear in Proceedings of IEEE Conference on Network Function Virtualization and Software Defined Networks, demo track, November, 2015

C25 S. Kadhe, Q. Zhang, M. Bakshi, S. Jaggi, and A. Sprintson, "Reliable and Secure Communication over Adversarial Multipath Networks," to appear in Proceedings of 10th International Conference on Information, Communications and Signal Processing (ICICS 2015), Singapore, Dec 2015

C26. M. Yan, J. Casey, P. Shome, A. Sprintson, and A. Sutton, "AetherFlow: Principled Wireless Support in SDN," in Proceedings of International Conference on Network Protocols (ICNP) CoolSDN workshop, San Francisco, CA, Nov 2015

C27. H. Lei, C. Singh, and A. Sprintson "Reliability Analysis of Modern Substations Considering Cyber Link Failures," in Proceedings of IEEE PES Innovative Smart Grid Technologies 2015 Asian Conference, Bangkok, Thailand, Nov 2015

C28. H. Kim, C. Singh, and A. Sprintson "Using Clustering to Evaluate Reliability of Composite Power Systems," In Proceedings of 2015 Intelligent System Applications to Power Systems Conference (ISAP 2015), Porto, Portugal, Sep 2015

C29. Q. Zhang, S. Kadhe, M. Bakshi, S. Jaggi, and A. Sprintson. "Coding Against a Limited-View Adversary: the Interplay Between Causality and Feedback," In Proceedings of 2015 IEEE International Symposium on Information Theory (ISIT), Hong Kong, SAR China, Jun 2015

C30. S. Kadhe, E. Soljanin, and A Sprintson, "Analyzing the Download Time of Availability Codes," In Proceedings of 2015 IEEE International Symposium on Information Theory (ISIT), Hong Kong, SAR China, Jun 2015

C31. C. Chan, A. Al-Bashabsheh, J. Ebrahimi, T. Kaced, S. Kadhe, T. Liu, A. Sprintson, M. Yan, and Q. Zhou. "Successive Omniscience," In Proceedings of 2015 International Symposium on Network Coding (NetCod), Sydney, Australia, Jun 2015

C32. M. Yu, A. Sprintson, and P. Sadeghi, "On Minimizing the Average Packet Decoding Delay in Wireless Network Coded Broadcast," In Proceedings of 2015 International Symposium on Network Coding (NetCod), Sydney, Australia, Jun 2015

C33 Q. Zhang, S. Kadhe, M. Bakshi, S. Jaggi, A. Sprintson. "Talking Reliably, Secretly, and Efficiently: A "Complete" Characterization." In Proceedings of Information Theory Workshop (ITW 2015), Jerusalem, Israel, Apr - May 2015

C34. M. Yan and A. Sprintson. "Approximation Algorithms for Erasure Correcting Data Exchange." In Proceedings of Information Theory Workshop (ITW 2015), Jerusalem, Israel, Apr - May 2015

C35 Gautam, N., Xu, Y. and Bradley, J.T. "Meeting Inelastic Demand in Systems with Storage and Renewable Sources," *Proc. of IEEE SmartGridComm*, 2014.

C36. M. Yan, A. Sprintson, and I. Zelenko. "Weakly Secure Data Exchange with Generalized Reed Solomon Codes." In Proceedings of the 2014 IEEE International Symposium on Information Theory (ISIT), Honolulu HI USA Jun - July 2014.

C37. M. Manjrekar, V. Ramaswamy and S. Shakkottai, " A Mean Field Game Approach to Scheduling in Cellular Systems," in IEEE Infocom 2014, Toronto, Canada, 2014.

C38. Rahul Singh, I-Hong Hou and P. R. Kumar, "Fluctuation Analysis of Debt Based Policies for Wireless Networks with Hard Delay Constraints," in Proceedings of IEEE INFOCOM 2014: The Conference on Computer Communications, pp. 24002408, Toronto, Ontario, Canada, April- May, 2014.

C39. Luoyi Fu, Xinbing Wang and P. R. Kumar, "Optimal determination of source-destination connectivity in random graphs," in Proceedings of The 15th ACM International Symposium on Mobile Ad Hoc Networking and Computing, ACM MobiHoc 2014, Philadelphia, August, 2014.

C40. S. Kadhe, S. Jaggi, M. Bakshi, and A. Sprintson. "Reliable, Deniable, and Hidable Communication over Multipath Networks." In Proceedings of the 2014 IEEE International Symposium on Information Theory (ISIT), Honolulu HI USA Jun - July 2014.

C41. A. Sprintson. "Reductions Techniques for Establishing Equivalence Between Different Classes of Network and Index Coding Problems," In Proceedings of Information Theory Workshop (ITW 2014), Hobart, Australia, Nov 2014.

C42. M. Manjrekar, V. Ramaswamy and S. Shakkottai, " A Mean Field Games Approach to Scheduling in Cellular Systems", Information Theory and Applications Workshop, San Diego, February, 2013

C43 S. Shakkottai, " Mean Field Games in Scheduling," in the Workshop on the Frontiers of Communication Networks: Theory and Algorithms, Bangalore, India, July 2013

C44. N. Abedini, S. Sampath, R. Bhattacharyya, S. Paul, and S. Shakkottai, "Realtime streaming with guaranteed QoS over wireless D2D networks," in Proc. of ACM MobiHoc, Bangalore, India, July 2013

C45 Rahul Singh, I-Hong Hou and P. R. Kumar, "Pathwise Performance of Debt Based Policies for Wireless Networks with Hard Delay Constraints," in Proceedings of 52nd IEEE Conference on Decision and Control, pp. 7838 7843, December 1013, 2013, Florence, Italy. (Invited Paper)

C46. Xueying Guo, Sheng Zhou, Zhisheng Niu and P. R. Kumar, "Optimal Wake-up Mechanism for Single Base Station with Sleep Mode," in Proceedings of the 25th International Teletraffic Congress (ITC 25), Shanghai, September 1012, 2013

C47. Y.-P. Hsu, I-H. Hou, and A. Sprintson, "The Index Coding Problem: A Game- Theoretical Perspective." In Proceedings of the 2013 IEEE International Symposium on Information Theory (ISIT), Istanbul, Turkey, July 2013

Conference presentations

P1. Kwon, S. and Gautam, N. "Demand-side Power Procurement with Renewable Generation and Energy Storage," INFORMS Annual Conference, Philadelphia, PA. (Presenter: Kwon), 2015

P2. Gautam, N. "Internet of Things: Challenges and Opportunities for Industrial Engineering," Industrial & Systems Engineering Research Conference, Nashville, TN. (Presenter: Gautam), 2015

P3 Gautam, N. "Managing Power Supply in Systems with Solar Panels and Storage", Industrial & Systems Engineering Research Conference, Nashville, TN. (Presenter: Gautam), 2015

P4. Gautam, N. "Managing Transmissions and Performance in Wireless Sensor Networks," Industrial & Systems Engineering Research Conference, Nashville, TN. (Presenter: Gautam), 2015

P5 Kwon, S. and Gautam, N. "Sizing Heterogeneous Servers with Non-stationary Arrivals for Time-stability," INFORMS Annual Conference, San Francisco, CA, 2014 (Presenter: Gautam)

P6. Ramaswamy, V., Gautam, N., Reddy, V., Shakkottai, S. and Sprintson, A. "Multipath Wireless Network Coding: An Augmented Potential Game," INFORMS Annual Conference, San Francisco, CA, 2014. (Presenter: Gautam)

P7. Sethuraman, S. and Gautam, N. "Fork Join Queues in In-network Function Computation," INFORMS Annual Conference, San Francisco, CA, 2014. (Presenter: Gautam)

P8. N. Gautam, "Performance Modeling and Approximations for Heterogeneous Servers," INFORMS Annual Conference, San Francisco, CA, 2014. (Presenter: Gautam)

P9. S. Kwon and N. Gautam, "Resource Management in Data Centers with Non-Homogeneous and Multi-class workload," INFORMS Annual Conference, Minneapolis, MN., 2013 (Presenter: Kwon)

P10. A. Mohapatra, N. Gautam, A. Sprintson, and S. Shakkottai "Network Coding Decisions for Wireless Transmissions with Delay Consideration," INFORMS Annual Conference, Minneapolis, MN., 2013 (Presenter: Mohapatra)

P11. S. Sethuraman and N. Gautam, "In-network Function Computation: Spanning Trees and Multi-class Fork-join Queues," INFORMS Annual Conference, Minneapolis, MN, 2013 (Presenter: Sethuraman)

P12. N. Gautam and S. Kwon, "Stabilizing Queues with Non-Homogeneous and Multi-class Workloads in Data Centers, INFORMS Applied Probability Society Conference," San Jose, Costa Rica, 2013, (Presenter: Gautam)

P13 A. Mohapatra, and N. Gautam "Efficiently Operating Energy-limited Wireless Nodes," INFORMS Applied Probability Society Conference, San Jose, Costa Rica, 2013 (Presenter: Gautam)

P14. A. Mohapatra, N. Gautam, A. Sprintson and S. Shakkottai, "Network Coding Decisions for Wireless Transmissions with Delay Consideration," INFORMS Annual Conference, Minneapolis, MN, 2013 (Presenter: Gautam)

Journal papers

J1. J-Y Won, P.V. Gratz, S. Shakkottai and J. Hu, Resource Sharing Centric Dynamic Voltage and Frequency Scaling for CMP Cores, Uncore and Memory. ACM Transactions on Design Automation of Electronic Systems (To Appear), 2015

J2. J. Li, R. Bhattacharyya, S. Paul, S. Shakkottai, V. Subramanian. A Mean Field Game Approach to Promoting Collaboration in Device to Device Networks. IEEE/ACM Transactions on Networking (To Appear), 2015

J3 Xueying Guo, Zhisheng Niu, Sheng Zhou and and P. R. Kumar, "Delay-Constrained Energy-Optimal Base Station Sleeping Control." To appear in *IEEE Journal on Selected Areas in Communications - Series on Green Communications and Networking (Issue 1)* .

J4. C. Chan, A. Al-Bashabsheh, Q. Zhou, N. Ding, T. Liu, and A. Sprintson "Successive Omniscience," to appear in the IEEE Transactions on Information Theory.

J5 Yan Gao, Chee Wei Tan, Shan Lin, Ying Huang, Zheng Zeng and P. R. Kumar, "Characterization and Optimization of Delay Guarantees for Real- time Multimedia Traffic Flows in IEEE 802.11 WLANs," to appear in IEEE Transactions on Mobile Computing.

J6. A. Marcum, J. Krogmeier, D. Love, and A. Sprintson. "Analysis and Implementation of Asynchronous Physical Layer Network Coding," IEEE Transactions on Wireless Communications, vol. 14, no. 12, pp. 6595-6607, Dec. 2015

J7. S. Kwon and N. Gautam. "Time-Stable Performance in Parallel Queues with Non-Homogeneous and Multi-class Workloads," to appear in the IEEE Transactions on Networking.

J8. Gong, S., Duan, L. and Gautam, N. "Optimal Scheduling and Beamforming in Relay Networks with Energy Harvesting Constraints," to appear in the IEEE Transactions on Wireless Communications, 2015

J9. Bjorkqvist, M., Gautam, N., Birke, R., Chen, L.Y. and Binder, W. "Optimizing for Tail Sojourn Times of Cloud Clusters," to appear in the IEEE Transactions on Cloud Computing, 2015

J10. Chan, W., Zhang, P., Nevat, I., Nagarajan, S., Valera, A., Tan, H. and Gautam, N. "Adaptive Duty Cycling in Sensor Networks with Energy Harvesting using CTMC and Fluid Models," IEEE Journal of Special Areas in Communications, Vol. 33, No. 12, 2687 - 2700, 2015

J11. Ying, Y., Birke, R., Wang, C., Chen, L.Y. and Gautam, N. "On Energy Aware Allocation and Execution for Batch and Interactive MapReduce," ACM SIGMETRCIS Performance Evaluation Review, Vol. 42, No. 4, 22-30, 2015

J12. S. Kwon and N. Gautam, "Guaranteeing Performance based on Time-stability for Energy-efficient Data Centers," IIE Transactions (to appear), 2015

J13 Jonathan Ponniah, Yih-Chun Hu and P. R. Kumar, "A System-Theoretic Clean Slate Approach to Provably Secure Ad Hoc Wireless Networking." To appear in IEEE Transactions on Control of Network Systems.

J14. Y.-P. Hsu, N. Abedini, N. Gautam, A. Sprintson, and S. Shakkottai, "Opportunities for Network Coding: To Wait or Not to Wait," IEEE Transactions on Networking, Vol. 23, No. 6, 1876 - 1889, 2015

J15 N. Gautam, A. Mohapatra, "Efficiently Operating Wireless Nodes Powered by Renewable Energy Sources," IEEE Journal of Special Areas in Communications, Vol. 33, No. 8, 1706 - 1716, 2015

J16. A. Mohapatra, N. Gautam, S. Shakkottai and A. Sprintson, "Optimal Network Coding Decisions in Delay-sensitive Wireless Transmission," IEEE Transactions on Communications, Vol. 62, No. 8, 2965-2976, 2014

J17. R.J. Polansky, S. Sethuraman, and N. Gautam, "Obtaining Optimal Thresholds for Processors with Speed-Scaling", Electronic Notes in Theoretical Computer Science, Vol. 310, 135-155, 2015

J18. S. Kwon, Y. Xu and N. Gautam, "Meeting Inelastic Demand in Systems with Storage and Renewable Sources," IEEE Transactions on Smart Grid (DOI: 10.1109/TSG.20152494874), 2015

J19. Kyoung-Dae Kim and P. R. Kumar, "An MPC-based Approach to Provable System-wide Safety and Liveness of Autonomous Ground Traffic." IEEE Transactions on Automatic Control, Special Issue on "Control of Cyber-Physical Systems." Vol. 59, no. 12, pp. 3341-3356, December 2014.

J20. K. J. Astrom and P. R. Kumar, "Control: A Perspective," Automatica, vol. 50, pp. 343, January 2014. Invited Paper.

J21. V. Reddy, V. Ramaswamy, S. Shakkottai, A. Sprintson, and N. Gautam, "Multipath Wireless Network Coding: A Population Game Perspective", IEEE/ACM Transactions on Networking, vol. 22, no. 1, pp. 217-229, Feb. 2014.

J22 Kyoung-Dae Kim and P. R. Kumar, "An Overview and Some Challenges of Cyber-Physical Systems." Journal of the Indian Institute of Science. pp. 341351, Vol. 93:3, July-September 2013

Journal papers (under review)

JR1. J. Ponniah, Y.-C. Hu and P. R. Kumar, "A Clean Slate Approach to Secure Ad Hoc Wireless Networking - Open Unsynchronized Networks." Submitted to *IEEE Transactions on Control of Network Systems: Special Issue on Secure Control of Cyber Physical Systems*.

JR2. B. Satchidanandan and P. R. Kumar, "Dynamic Watermarking: Active Defense of Networked Cyber-Physical Systems." Submitted to *Proceedings of the IEEE*. Submitted January 10, 2016.

JR3 G.L. Jones, P.G. Harrison, and N. Gautam, "Analyzing a Tandem Fluid Network with Cross-traffic," Submitted to IEEE Transactions On Networking.

JR4. Luoyi Fu, Xinbing Wang and P. R. Kumar, "Are we connected? Optimal determination of source-destination connectivity in random graphs." Submitted to IEEE/ACM Transactions on Networking.

Working papers

W1. K. Ma, L. Xie and P. R. Kumar, "A Layered Architecture for EV Charging Stations Based on Time Scale Decomposition." Submitted to *IEEE Transactions on Control of Network Systems*.

W2. J. Ponniah, Y.-C. Hu and P. R. Kumar, "A Clean Slate Approach to Secure Ad Hoc Wireless Networking - Open Unsynchronized Networks." Submitted to *IEEE Transactions on Control of Network Systems: Special Issue on Secure Control of Cyber Physical Systems*.

W3 M. Rafieisakhaei, A. H. Tamjidi, S. Chakravorty and P. R. Kumar, "Feedback Motion Planning Under Non-Gaussian Uncertainty and Non-Convex State Constraints." Submitted to *IEEE International Conference on Robotics and Automation (ICRA 2016)*, May 16-21, 2016, Stockholm, Sweden.

W4. Bharadwaj Satchidanandan and P. R. Kumar, "Dynamic Watermarking: Active Defense of Networked Cyber-Physical Systems." Submitted to *Proceedings of the IEEE*. Submitted January 10, 2016.

W5 Luoyi Fu, Xinbing Wang and P. R. Kumar, "Are we connected? Optimal determination of source-destination connectivity in random graphs." Submitted to IEEE/ACM Transactions on Networking.

W6. Sethuraman, S and Gautam, N. "Arborescence-packing for In-Network Function Computing." (under revision)

W7. Sethuraman, S and Gautam, N. "Fork-Join Queues: New Results for Symmetric Case with Applications in Communication Systems;" (under revision)

W8. I-Hong Hou, Yao Liu, and Alex Sprintson, "Distributed Device-to-Device Content Distribution with Strategic Users," to be submitted to IEEE/ACM Transactions on Networking.

W9. J. Li, B. Xia, X. Geng, H. Meng, S. Shakkottai, V. Subramanian and L. Xie, "Mean Field Games in Nudge Systems for Societal Networks," submitted to INFORMS Journal of Operations Research.

W10. N. Abedini, R. Bhattacharyya, S. Paul, K-Y Lee, S. Sampath and S. Shakkottai, "Realtime streaming with guaranteed QoS over wireless D2D networks," to be submitted to IEEE/ACM Transactions on Networking

Students supported

Graduated

- Pradipta Bose, M.S., "StorageFlow: an SDN Approach to Storage Networks," August 2014, now at HP (Aruba networks)
- Samyukta Sethuraman, "On Fork-join Queues and Maximum Ratio Cliques", December 2015 (Amazon)
- Daoqi Wang, M.S., "Design, Conformance Verification, and Performance Evaluation of OpenFlow Message Layer," May 2014, now at HP (Aruba networks)
- Rahul Singh "Index Policies for Optimal Mean- Variance Trade-Off of Inter-delivery Times in Real-Time Sensor Networks," Oct. 2015, now at MIT (postdoc)
- Raghdah Al Shaikhi, M.S., "MobileFlow: Applying SDN to Mobility in Wireless Networks," August 2014, now at CISCO
- Vinod Ramaswamy, Ph.D., "Applications of Game Theory to Multi-agent Coordination Problems In Communication Networks", August 2013, now a Postdoctoral associate at the University of Colorado at Boulder.
- Yu-Pin Hsu, Ph.D, "Wireless Network Coding: Analysis, Control Mechanisms, and Incentive Design," May 2014, now a postdoc at Massachusetts Institute of Technology.
- Suman Paul, M.S., "Realtime Streaming with Guaranteed QoS Over D2D Wireless Networks," August 2014, now at CISCO
- Arupa Mohapatra, Ph.D., "Energy Management in Wireless Sensor Network Operations", August 2013, now at Oracle.
- Atin Ruia, M.S., "FlowCache: A Cache for Software Defined Networking," August 2015, now at Microsoft.
- Yao Liu, M.S., "A Packet Scheduling Mechanism for Wireless Peer-To-Peer Content Distribution", December 2013, joined Intel.

Current students

- Jian Li
- Rajarshi Bhattacharyya
- Gaurav Sharma
- Mohammadhussein Rafieisakhaei
- Ke Ma
- Jaeyong An
- Xi Liu
- Bharadwaj Satchidanandan
- Simon Yau
- Vamseedhar Reddivari
- Ki-Yeob Lee
- Woo Hyun Ko

- Simon Yau
- Bainan Xia
- Vamseedhar Reddyvari
- Ki-Yeob Lee
- Swanand Kadhe
- Muxi Yan
- Corey Morrison
- Soongeol Kwon
- Jasson Casey
- Jin Xu
- Sudarshan Rajan

Keynotes/Plenaries/Distinguished Seminars

- Rockwell Distinguished Seminar, University of Houston, January 29, 2016. (Kumar)
- Keynote Talk, *IEEE Real-Time Systems Symposium (RTSS 2015)*, San Antonio, December 1-4, 2015 (Kumar)
- Keynote Speaker, *1st International Conference on Big Data Computing and Communication (BigCom 2015)*, Tai Yuan, China, August 1–3, 2015 (Kumar)
- Keynote Speaker, *34th Chinese Control Conference (CCC) and Society of Instrument and Control Engineers (SICE) of Japan Annual Conference 2015 (SICE 2015)*, Hangzhou, China, July 28–30, 2015 (Kumar)
- Keynote Speaker, *150th Anniversary Celebrations of ITU*, Bangalore, July 9, 2015 (Kumar)
- Keynote Speaker, *11th International Workshop on Resource Allocation, Cooperation and Competition in Wireless Networks (RAWNET 2015)*, Mumbai, India, May 25, 2015 (Kumar)
- Keynote Speaker, 2014 IEEE Vehicular Networking Conference (VNC) Paderborn, Germany, December 3-5, 2014 (Kumar)
- Keynote Speaker, Cyber-Physical Systems Week (CPSWeek) 2014. Berlin, Germany, April 15-17, 2014 (Kumar)
- Keynote Speaker, IEEE International Conference on Computer Communications (INFOCOM 2014) Toronto, Canada, April 27-May 2, 2014 (Kumar)
- Plenary Speaker, Twentieth National Conference on Communications (NCC), Kanpur, India, Feb 28, 2014 (Kumar)
- Distinguished Visitor Talk, Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada, Jan 27, 2014 (Kumar)
- Plenary Speaker, *2013 Annual IEEE India Conference (INDICON)*, Bombay, Dec 15, 2013 (Kumar)

- Keynote Speaker, *The Fourth International Workshop on Cross-Layer Design (IWCLD 2013)*. Qingdao, China, Oct 28–29, 2013 (Kumar)
- Keynote Speaker, *2013 International Conference on Wireless Communications and Signal Processing (WCSP 2013)*. Hangzhou, China, Oct 24–26, 2013 (Kumar)
- Computer Science Distinguished Speakers Series, College of William and Mary, Williamsburg, VA, October 18, 2013 (Kumar)
- Keynote Speaker, *IEEE Wireless Communications and Networking Conference (WCNC 2013)*, Shanghai, China, April 7–10, 2013 (Kumar)
- NSF CISE Distinguished Lecture, February 6, 2013 (Kumar)
- Keynote Talk at *International Conference on Computing, Networking and Communications (ICNC)*, San Diego, January 29–31, 2013 (Kumar)

Honors Received During the Period of the Award

- 2016 IEEE INFOCOM Achievement Award (the highest honor that can be bestowed on a researcher in the INFOCOM community. The recipient should have a body of work that has had significant impacts on the networking community in general, and INFOCOM in particular.) (Kumar)
- 2015 Engineering Outstanding Contribution Award, Texas A&M University College of Engineering (Sprintson)
- Awarded IEEE Senior Membership, March 2015, Institute of Electrical and Electronics Engineers (Shakkottai)
- Texas A&M University Distinguished Professor, 2014 (Kumar)
- Texas A&M Engineering Experiment Station Select Young Faculty Fellowship 2014 (Shakkottai)
- Finalist, INFORMS Telecom Section Best Paper Award, 2014 (Gautam, Sprintson, Shakkottai)
- Open Networking Foundation (ONF) driver competition, runner-up (Sprintson)
- Student (Samyukta Sethuraman) awarded the "MP2 Energy Institute Fellowship", September 2014 (Gautam)
- International Conference on Network Protocols, International Conference on Network Protocols (ICNP) CoolSDN workshop, Best paper Award 2014 (Sprintson)
- Air Force Summer Faculty Fellowship, Air Force Research Lab, 2014 (Sprintson)
- National Science Foundation (NSF) ScienceLives video interview series, 2014 (Kumar)
- Named the Jill and Charles F. Milstead'60 Faculty Fellow (endowed fellowship appointment), May 2013 to April 2015 (Gautam)

- Awarded IEEE Senior Membership, August 2013, Institute of Electrical and Electronics Engineers (Gautam)
- 2013 ACM Fellow, Association for for Computing Machinery (Kumar)
- Research highlighted in Industrial Engineer magazine (for potentially impactful journal articles among those that appear in IIE Transactions), September 2013 (Gautam)
- Student (Arupa Mohapatra) awarded the "2013 U.S. Senator Phil Gramm Doctoral Fellowship award for contributions in research, teaching and mentoring", March 2013 (Texas A&M University-wide recognition, Gautam)

Books and Book Chapters

B1. J. Ponniah, Y.-C. Hu and P. R. Kumar, "A Clean Slate Approach to Secure Wireless Networking". Vol. 9: No. 1, Foundations and Trends in Networking, NOW Publishers, Delft, The Netherlands, 2015

B2. S. Shakkottai and R. Srikant, "Communication Networks: Pricing, Congestion Control, Routing and Scheduling." in the Handbook of Game Theory, T. Basar, eds. Springer, to appear, 2016.

B3 A. Sprintson and A. Orda, "Algorithms for Finding Disjoint Paths with QoS Constraints." In the Handbook of Graph Theory and Algorithms, K. Thulasiraman, eds. CRC press, expected publication date Dec 2015

Invited Seminars/Talks

1. Distinguished Mercer Lecture, Rensselaer Polytechnic Institute, November 30, 2016 (Kumar)
2. Keynote Speaker, The 13th IEEE International Conference on Mobile Ad hoc and Sensor Systems (IEEE MASS 2016), October 1013, 2016, Brasilia, Brazil (Kumar)
3. Plenary Lecture, 6th IFAC Workshop on Distributed Estimation and Control in Networked Systems (NecSys 2016), September 8-9, 2016, Tokyo, Japan (Kumar)
4. ECE Speaker Series Seminar, University of Houston, January 29, 2016 (Kumar)
5. Keynote Talk, IEEE Real-Time Systems Symposium (RTSS 2015), San Antonio, December 1-4, 2015(Kumar)
6. Keynote Speaker, 1st International Conference on Big Data Computing and Communication (BigCom 2015), Tai Yuan, China, August 13, 2015 (Kumar)
7. Keynote Speaker, 34th Chinese Control Conference (CCC) and Society of Instrument and Control Engineers (SICE) of Japan Annual (Kumar)
8. Conference 2015 (SICE 2015) Hangzhou, China, July 2830, 2015 (Kumar)
9. Keynote Speaker, 150th Anniversary Celebrations of ITU, Bangalore, July 9, 2015 (Kumar)

10. Keynote Speaker, 11th International Workshop on Resource Allocation, Cooperation and Competition in Wireless Networks (RAWNET 2015), Mumbai, India, May 25, 2015 (Kumar)

11. Keynote Speaker, CPS Workshop, Design Automation Conference, Austin, TX, June 5, 2016 (Kumar)

12. "Mean Field Games: An Approach to Understanding Resource Sharing Systems," Network Science Seminar at Arizona State University, March 2015 (Shakkottai)

13. Invited Talk: "Managing operations for consumers with energy storage, stochastic demand and renewable supply," Penn State Univ. OR Colloquium, State College, PA, October 2015 (Gautam)

14. Tutorial: "Mean Field Games in Societal Networks," IPAM Graduate Summer School: Games and Contracts for Cyber-Physical Security, July 2015 (Shakkottai)

15. Seminar: "An Auction Theoretic Approach to Scheduling in Cellular Networks", Indian Institute of Science, Bangalore, India. June 2015 (Shakkottai)

16. Seminar: Mean Field Games in Societal Networks, IBM Research, Bangalore, India, June 2015 (Shakkottai)

17. Talk: "Cooperative Data Exchange with Deadlines," Mathematical Coding Theory in Multimedia Streaming Workshop, Banff International Research Station for Mathematical Innovation and Discovery, Banff, Canada, October 2015 (Sprintson)

18. Seminar: "Applications of Software Defined Networking (SDN) in Wireless Aerial Networks," Air force Research Lab, Rome Research Site, Aug 2015, Rome, New York (Sprintson)

19. Keynote presentation: "Advanced Coding Schemes for Improving Network Reliability and Security," 7th Central Area Networking and Security Workshop, Kansas City, Missouri, Mar 2015 (Sprintson)

20. Tutorial: "Advanced Coding Schemes for Improving Network Reliability" - Design of Reliable Communications Networks Conference (DRCN 2015), Mar 2015, Kansas City, Missouri, USA (Sprintson)

21. Tutorial: "Introduction to Wireless Network Coding," The San Paulo Coding School, Campinas, Brazil, Jan 2015 (Sprintson)

22. Webinar: "Applications of Software-Defined Networking (SDN) in Power System Communication Infrastructure: Benefits and Challenges," Power Systems Engineering Research Center (PSERC), Feb. 2015 (Sprintson)

23. Presentation "MDS Codes with Constrained Generator Matrices and Related Problems," Banff International Research Station (BIRS), Workshop on Network Information Theory and Combinatorics at the Banff International Research Station for Mathematical Innovation and Discovery (BIRS), Banff, Canada, March 2015 (Sprintson)

24. Invited talk: "Towards Universal Weakly-Secure Codes for Data Exchange and Storage," DIMACS Workshop on Coding Theoretic Methods for Network Security, DIMACS Center, Rutgers University. Apr 2015 (Sprintson)

25. Seminar: "Mean Field Games: An Approach to Understanding Resource Sharing Systems", UC San Diego, Dept. of ECE, December, 2014 (Shakkottai)

26. Keynote Speaker, 2014 IEEE Vehicular Networking Conference (VNC) Paderborn, Germany, December 3-5, 2014 (Kumar)

27. Keynote Speaker, Cyber-Physical Systems Week (CPSWeek) 2014. Berlin, Germany, April 15-17, 2014 (Kumar)

28. Keynote Speaker, IEEE International Conference on Computer Communications (INFOCOM 2014) Toronto, Canada, April 27May 2, 2014 (Kumar)

29. Plenary Speaker, Twentieth National Conference on Communications (NCC), Kanpur, India, Feb 28, 2014 (Kumar)

30. Distinguished Visitor Talk, Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, Canada, Jan 27, 2014 (Kumar)

31. "Wireless Network Coding: Algorithms, Analysis, and Applications," Institute for Network Coding, Chinese University of Hong Kong, Hong Kong, China, November 2014 (Sprintson)

32. LatentView (Executive Seminar), Chennai, India, "Managing Operations in Time-Varying Systems", June 2014 (Gautam)

33. POSTECH University (Industrial and Management Engineering Seminar), Pohang, South Korea, "Managing Operations in Systems with Energy Storage, Stochastic Demand and Renewable Supply," April 2014 (Gautam)

34. Institute for Infocomm Research (Sense and Sense-abilities Group), Singapore, "Multi-timescale Model for Wireless Nodes with Energy Harvesting," April 2014 (Gautam)

35. Singapore University of Technology and Design (Wireless Networks and Decision Systems Group), "Multi-timescale Model for Wireless Nodes with Energy Harvesting," April 2014 (Gautam)

36. Singapore University of Technology and Design (Engineering Systems Design Pillar), "Managing Time-Varying Systems with Applications in Healthcare and Energy," April 2014 (Gautam)

37. National University of Singapore (Decision Sciences Seminar), "Managing Power Supply in Systems with Renewable Energy Sources," April 2014 (Gautam)

38. National University of Singapore (Industrial and Systems Engineering Seminar), "Multi-timescale Model for Wireless Nodes with Energy Harvesting," March 2014 (Gautam)

39. "Practical Information-Theoretic Security for Wireless and Data Storage Networks," University of New South Wales, Sydney, Australia, November 2014 (Sprintson)

40. "Practical Information-Theoretic Security for Wireless and Data Storage Networks," HongKong University, Hong Kong, China, November 2014 (Sprintson)

41. Tutorial: "Learn the details of OpenFlow with Interactive Switch Visualization," Global Communications Conference (Globecom), December 2014 (Sprintson)

42. Tutorial: "Network Coding: Fundamentals and Applications," Air Force Research Lab (AFRL), Rome research site, Rome, NY, July 2014 (Sprintson)

43. Plenary Speaker, 2013 Annual IEEE India Conference (INDICON), Bombay, Dec 15, 2013 (Kumar)

44. Keynote Speaker, The Fourth International Workshop on Cross-Layer Design (IWCLD 2013) Qingdao, China, Oct 2829, 2013 (Kumar)

45. Keynote Speaker, 2013 International Conference on Wireless Communications and Signal Processing (WCSP 2013) Hangzhou, China, Oct 2426, 2013 (Kumar)

46. Computer Science Distinguished Speakers Series, College of William and Mary, Williamsburg, VA, October 18, 2013 (Kumar)

47. Keynote Speaker, IEEE Wireless Communications and Networking Conference (WCNC 2013), Shang- hai, China, April 710, 2013 (Kumar)

48. NSF CISE Distinguished Lecture, February 6, 2013 (Kumar)

49. Keynote Talk at International Conference on Computing, Networking and Communications (ICNC), San Diego, January 2931, 2013 (Kumar)

50. Bristol University (Probability and Statistics Seminar), Mathematics Department, Bristol, United Kingdom, *Two-tier Model for Balancing Power and Performance in Renewable-Energy-Based Wireless Nodes*, November 2013 (Gautam)

51. Lancaster University (Statistics and Operations Research Seminar), Management Science Department, Lancaster, United Kingdom, *Multi-timescale Model for Wireless Nodes Powered by Renewable Energy Sources*, November 2013 (Gautam)

52. IBM Research (Zurich Research Laboratory), Zurich, Switzerland, *Stabilizing Queues with Non-Homogeneous and Multi-class Workloads in Data Centers*, November 2013 (Gautam)

53. Budapest University of Technology and Economics (Department of Networked Systems and Services), Budapest, Hungary, *Efficiently Operating Wireless Nodes Powered by Renewable Energy Sources*, October 2013 (Gautam)

54. Newcastle University (Department of Computing Science), Newcastle, United Kingdom, *Managing energy harvesting wireless networks*, October 2013 (Gautam)

55. University of Edinburgh (ERGO Seminar, School of Mathematics), Edinburgh, United Kingdom, *Multi-tier model for managing power and performance in renewable-energy-based wireless nodes*, October 2013 (Gautam)

56. Imperial College (AESOP Lab, Department of Computing), London, United Kingdom, *Managing energy harvesting wireless networks*, September 2013 (Gautam)

57. University of California-Berkeley (ORIE seminar), Berkeley, CA, *Stabilizing Queues with Non-Homogeneous and Multi-class Workloads for Effective Analysis and Control*, February 2013 (Gautam)

58. Los Alamos National Lab, Los Alamos, NM, Center for Non-Linear Studies (Smart-Grid Seminar Series), *Resource Management under Non-Homogeneous and Multi-class Workloads in Data Centers*, January 2013 (Gautam)

59. Tutorial: "Index coding: fundamentals, applications, and recent progress, " Dagstuhl Coding Theory Seminar, Leibniz Center for Informatics, Aug 2013 (Sprintson)

60. Tutorial: "Index Coding: Algorithms and Relation to Network Coding," 2013 IEEE International Symposium on Network Coding, Calgary, Canada, Jun 2013 (Sprintson)

61. Tutorial: "Wireless Network Coding: Algorithms and Applications," Military Communications Conference (Milcom' 2013), San Diego, CA, Nov. 2013 (Sprintson)

62. Seminar: "Distributed Data Exchange with Weak Security," Banff International Research Station (BIRS), Banff, Alberta, Canada, Sept 2013 (Sprintson)

63. Seminar: "Stochastic Pre-Classification for Software-Defined Firewalls," Air Force Research Lab (AFRL), Rome research site, Rome, NY, July 2013 (Sprintson)

1.

1. Report Type

Final Report

Primary Contact E-mail

Contact email if there is a problem with the report.

spalex@tamu.edu

Primary Contact Phone Number

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9794580092

Organization / Institution name

Texas A&M University

Grant/Contract Title

The full title of the funded effort.

A Holistic Approach to Networked Information Systems Design and Analysis

Grant/Contract Number

AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-13-1-0008

Principal Investigator Name

The full name of the principal investigator on the grant or contract.

P. R. Kumar

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. Kathleen Kaplan

Reporting Period Start Date

01/15/2013

Reporting Period End Date

01/14/2016

Abstract

The work funded under this award established methods and tools for secure and timely delivery of information over wireless communication networks. Our methods enable the wireless networking and storage systems to provide provable performance guarantees for a variety of diverse applications that impose strict delay, throughput, reliability, and availability requirements. Our contribution includes provably secure wireless networking protocols as well as a methodology for design and analysis of provably correct and safe design of heterogeneous systems. We have designed mechanisms that ensure insensitivity to strategic gaming and security against malicious adversaries. Our research paves the way to a holistic theory that unifies a range of mathematical, system-theoretic, and optimization tools. Our research will have a major impact on future aerial systems that will support secure, robust, and delay-sensitive applications.

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Archival Publications (published) during reporting period:

Changes in research objectives (if any):

N/A

Change in AFOSR Program Manager, if any:

Current Program Manager is Dr. Kathleen Kaplan

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

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Appendix Documents

2. Thank You

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